Shallow-Water Propagation

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LONG-TERM GOALS

Develop models and methods for propagation and coherence calculations in complex shallow-water environments, determine their capabilities and accuracy, and apply them for simulating and understanding experimental data.

OBJECTIVES

(A) Treat propagation from narrowband and broadband sources over elastic and poro-elastic sediments, and incorporate influences of realistic bathymetry and geoacoustic layering.

(B) Analyze and model data, quantify effects of random environmental and experimental variability, and determine efficiently field statistics for intensity and coherence.

APPROACH

(A) Devise high accuracy PE techniques for applications to shallow-water sediments that may be anisotropic and dispersive. Treat range dependence and layering by mapping and energy conservation methods. Benchmark results using independent computational procedures.

(B) Develop environmental models for ocean and geoacoustic variability using data and efficient representations. Perform field calculations with PE, normal mode, and perturbation methods. Investigate predictability using model predictions and independent data sets.

- Principal collaborators are: Rensselaer graduate students and recent graduates; Dr. Michael Collins (NRL) for model development; and Dr. William Carey (BU), Dr. James Lynch (WHOI), and Dr. Mohsen Badiey (Delaware) for analysis and simulation of experimental data.

WORK COMPLETED

(A) We produced new illustrations demonstrating that our elastic PE formulation [1] accurately and efficiently treats propagation problems through layered sediments, including Rayleigh, Scholte, and

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14. ABSTRACT
Develop models and methods for propagation and coherence calculations in complex shallow-water environments, determine their capabilities and accuracy, and apply them for simulating and understanding experimental data.

15. SUBJECT TERMS

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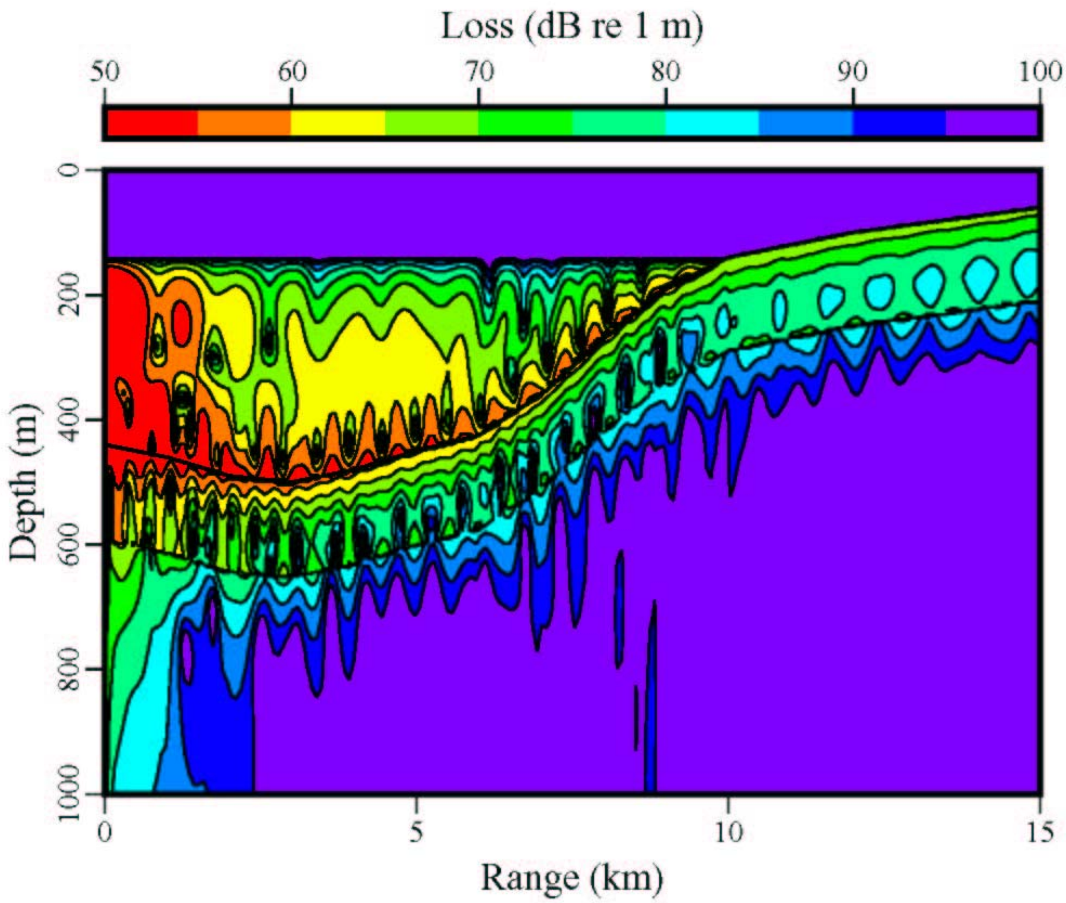
Stoneley interface waves. This formulation, extended using energy conservation techniques, provides the only current method for handling weakly range-dependent elastic sediments along with interfacial waves on variable interfaces [2]. Complex environments, with features such as beaches, shelves, and sandbars, can now be treated [3] by a combination of our formulation and a mapping approach. A recent generalization using successive applications of rotated PE computations is being completed [4] for accurate calculations in steeply sloped regions. Comparisons of these methods are being made [5] with elastic media formulations containing improved approximations for energy conservation and single scattering. In propagating broadband pulses through elastic sediments, we discovered several effects [6] of causal dispersion that arise from frequency-dependent attenuation. Computations were performed to quantify the resolvability of the directional dependence of wave speeds in transversely isotropic (TI) elastic sediments [7] using wave number spectra. We obtained new approximations for sound speeds in TI poro-elastic sediments and showed how the anisotropy influences propagation using our computational model [8]. We demonstrated that both high efficiency and accuracy can be achieved for PE computations at relatively high frequencies [9] in a variety of shallow-water environments.

(B) Broadband modeling simulations of data from one southwest propagation track in the SWARM95 experiment demonstrated [10] that resonant coupling between acoustic modes and internal solitons produce the time oscillations in observations of pulse-integrated energy. Sensitivity examinations of soliton parameters and geoacoustic profiles showed that this coupling mechanism is sufficiently robust, and is also supported by observed correlations between thermal and intensity statistics [11]. In contrast, observed time variations from another southwest track were shown [12] to arise from horizontal energy refraction due to ducting by the soliton wave fronts, an effect that has been conjectured but never previously demonstrated in measurements. The occurrence of this mechanism in other coastal regions possessing significant ocean variability is being investigated [13], with particular attention to influences of random variability of the solitons. Simulations of independent narrowband and broadband data from the ACT III experiment in the Strait of Korea required nonlinear frequency dependence of the upper sediment layer attenuation [14], and this result was shown to significantly influence estimates of the transverse coherence length. The shallow-water coherence degradation in this region proved to be dominated by water column and bathymetric variations [15], from an analysis using adiabatic mode and perturbation methods. These results were extended to other shallow water regions [16], with new calculations to verify applicability and specify limitations. Another example is the AGS site off New Jersey where substantial environmental and acoustic data is available, and again the role of nonlinear frequency dependence in attenuation was substantial [17].

RESULTS (from two selected investigations)

- Shallow-water propagation problems may involve acoustic energy interactions between the ocean, different types of sediment, and even other features such as beaches and sandbars. These inherently range-dependent problems provide a strenuous challenge for previous propagation methods. Our PE formulation for elastic sediments [2] allows regions with sufficiently small slope changes to be handled accurately and efficiently. A recent extension using a mapping approach [3] applies to shallow-water environments with complex layering and steep slopes, and requires only that the rate of slope changes is sufficiently gradual. Acoustic energy exchanges that result from range evolution of interfaces are demonstrated to have significant impacts on propagation characteristics. An illustration is the transmission-loss contour plot in **Figure 1,** showing an ocean over an elastic sediment which is above an elastic basement, and the water-sediment bathymetry rises to the surface to form a beach. A Scholte

wave develops near the bathymetric interface and propagates up the slope to the start of the beach, where the wave energy transitions into a Rayleigh wave near the air-sediment boundary. A significant portion of the energy in this low-frequency example persists as it propagates inside the sediment layer and up the beach. We conclude that this new method offers unique capabilities for investigating propagation interactions, including wave conversion mechanisms, between the ocean and sediment layers.



<u>Figure 1</u>. Many propagation problems involving range-dependent transitions between water and elastic sediments can be handled efficiently and accurately using a hybrid PE approach. Transmission loss contours, to 1000 m in depth and 15 km in range for a 5 Hz source, are shown for a model beach environment. The ocean depth is 300 m at the initial range (where the source is 5 m above the bottom), then increases to a maximum of 360 m at about 3 km, and finally decreases with variable slope to zero at 10 km. An elastic sediment layer is 150 m thick and follows the bathymetry for the first 10 km, after which its upper surface forms a beach that rises with uniform slope to 80 m above sea level at 15 km. The sediment layer has compressional and shear sound speeds of 2400 and 1200 m/s, corresponding attenuations of 0.05 and 0.1 dB/λ, and density 1.5 gm/cm^3. The basement below the elastic layer has higher sound speeds and density. The contours illustrate a conversion between interfacial wave types. A Scholte wave develops at the water-sediment bathymetry, and the energy in this wave moves into a Rayleigh wave at the air-sediment boundary.

- Recent major experiments confirmed that large-amplitude internal solitons in many shallow-water environments significantly affect acoustic variability. In the SWARM95 experiment, the same broadband air gun signals were sent along one pair of experimental tracks. The essential distinction is that the tracks made different angles with wave fronts of dominant internal solitons that were traversing them. Along one track we found [10] that the source of observed variations in received signals was coupling between wavenumbers from soliton energy spectrum peaks and from differences in principal acoustic modes. Along the other track, for which the aforementioned angle was small, the variability was produced from energy focusing and defocusing that was caused by the soliton wave fronts [12]. An example is shown in **Figure 2**, where the left panel [black curves] displays filtered pulses observed at one hydrophone on the WHOI VLA about 15 km away from the source. The right panel [blue curves] compares corresponding simulations from an adiabatic mode PE, using an environmental model containing a train of eight solitons. Both observations and computations show similar features, in time variability of pulse amplitude and second-mode arrival times, that arose from the passage of the solitons. We conclude that the mechanism of horizontal refraction produced by strong oceanic variability, which was studied by several previous researchers but never previously documented in experimental data, can occur in shallow water and cause pulse-integrated energy variations of about 6 dB.

IMPACT/APPLICATIONS

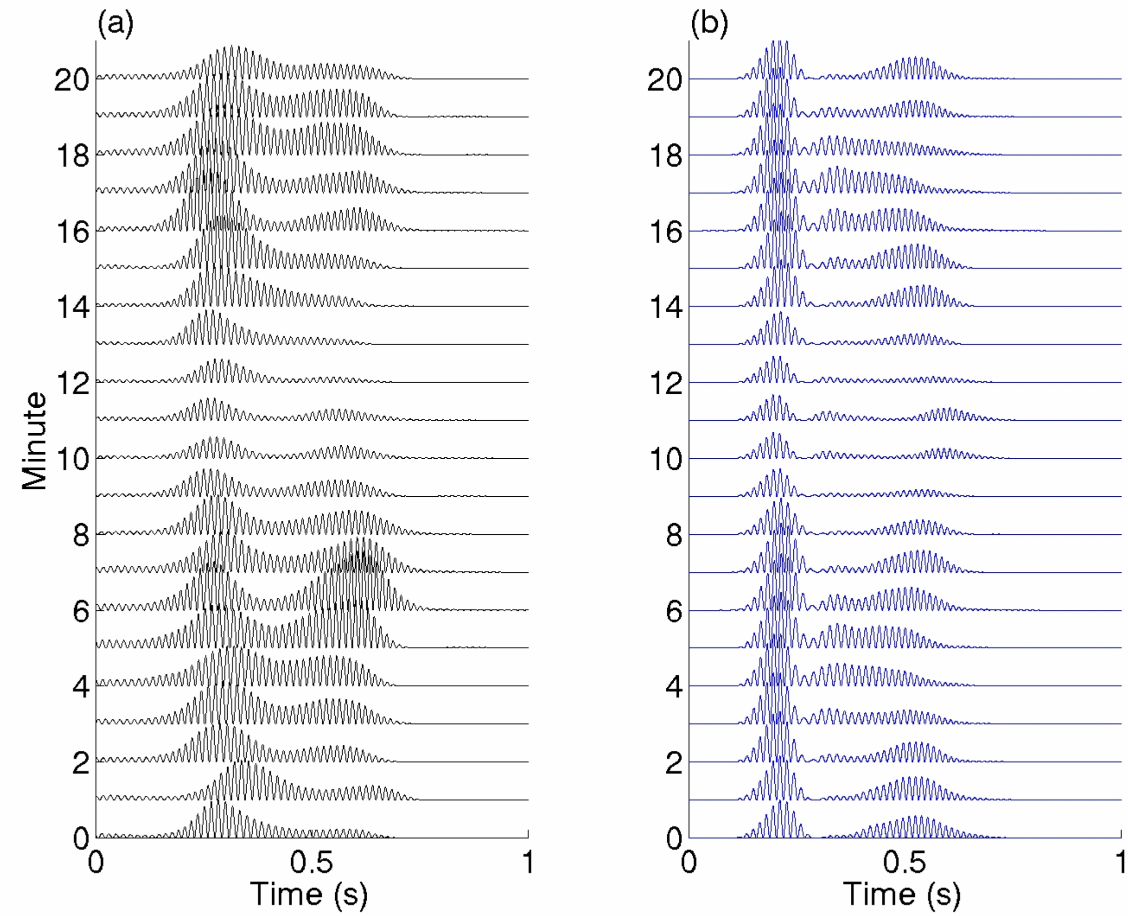
New or improved capabilities for handling shallow-water sediment physical properties, including elasticity, porosity, anisotropy, and dispersion, will be available for propagation predictions. Sediment interfacial variability, including range-dependent bathymetry and layer boundaries, will be accurately treated for predictions. High frequency, full wave, range-dependent propagation calculations will be practical. Efficient specification of intensity and coherence statistics resulting from environmental fluctuations and experimental variability will be feasible. Data analyses and comparisons will allow determination, for experimental data and for applications, of the relative significance of physical mechanisms, including linear versus nonlinear frequency dependence of attenuation, water column versus bathymetric variability, and vertical versus horizontal coupling due to internal solitons. Results from modeling and data analyses of several experiments (HCE, AGS, ACT, SWARM) are directed partly toward improving shallow-water sonar systems and predictions. New propagation model implementations, data representation techniques, and analysis tools have been distributed to university and laboratory research groups.

RELATED PROJECTS

- Additional work with Dr. Michael Collins includes completion of a research monograph on state of the art PE models and applications [18].

- Further research with Dr. Mohsen Badiey and Dr. James Lynch focuses on acoustic consequences of azimuthal variability in shallow water, including heterogeneous sediments with complex stratigraphy [19] and propagating internal solitons [20].

- Current work with Dr. William Carey examines predictability of narrowband and broadband propagation properties, including coherence scales and incorporating influences of the frequency dependence of sediment attenuation. Supported by Graduate Traineeship Award 0238.



<u>Figure 2</u>. Horizontal refraction of acoustic energy can be identified, using PE computations, as the mechanism that produces time variability of observed broadband signals. During the SWARM95 experiment, signals from an air gun source on R/V Cape Hatteras were received at the WHOI VLA. Each black or blue curve shows the amplitude of the signal at hydrophone 2, at depth 19 m, over a one-second window. Each curve is the filtered output from a 10-Hz band centered at 32 Hz. Each column of curves corresponds to shots every minute during a twenty-minute window. <u>Left panel</u>: Black curves are observational data showing two mode arrivals. Amplitudes of both modes increase to relatively large values during the first seven minutes, then over the next seven minutes decrease to much smaller values (by about a factor of three for mode 1, ten for mode 2), and finally return to large values over the last six minutes. The second-mode-arrival delay times are initially short, then increase, and finally decrease. The variations in signal amplitude correspond to those seen in the pulse-integrated energy, which are about 6 dB. <u>Right panel</u>: Blue curves are from PE simulations when internal solition wave fronts form an angle of 3 degrees with the propagation track. The variability in simulation amplitudes and delay times show the same features (with less noise) as data.

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PUBLICATIONS

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